

Senior Thesis

Hydrology of the Barbados Ridge Complex,
Lesser Antillies Accretionary Complex

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ABSTRACT

The Barbados Ridge Complex is the easternmost portion of the Lesser Antillies Subduction Complex. At the deformation front forming its eastern boundary sediment is scraped off of the Atlantic Plate and accreted to the Caribbean Plate. Seismic profiles show that the sediments comprising the Barbados Ridge Complex are divided into an upper, deformed sequence and a lower, layered sequence separated by a decollement. In attempts to penetrate the decollement DSDP Leg 78A and ODP Leg 110 encountered high pore fluid pressures, temperatures and methane concentrations. Pressures of up to 350 psi and 20.4°C were encountered at Sites 542 and 541, respectively.

As the sediments are accreted to the overriding plate tectonic compression forces dewatering of the earliest accreted sediments. Due to the low permeability of the oceanic muds and clays, water is expelled along the decollement and thrust faults splaying from it. This water transmits heat from within the prism to the sediment-water interface. This expelled pore fluid concentrates thermogenic methane along these conduits, where oxidation of the methane within the sulfate reducing zone causes the precipitation of carbonates. As a byproduct hydrogen sulfide is produced, implying the possible existence of vent communities similar to those reported off the Oregon coast.

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INTRODUCTION

The study of active convergent plate margins has been greatly enhanced by developments in deep-water drilling methods. This has allowed the direct observation of the deformational and diagenetic processes occurring within these complexes. One of these complexes is the Barbados Ridge Complex. Both Deep Sea Drilling Project (DSDP) Leg 78A and Ocean Drilling Project (ODP) Leg 110 cored the sediments of the Barbados Ridge along an east-west line near 15°30N. In addition, ODP Leg 110 sampled a site along this line east of the deformation front as an oceanic reference (Masle, Moore and others, 1987). DSDP Leg 78A also sampled an oceanic reference site somewhat to the north of the other sites (Biju-Duval, Moore and others, 1984). The area of the complex sampled is roughly 250 km north-northeast of Barbados and 260 km east of the Lesser Antillies Arc, which marks the approximate eastern margin of the Caribbean Plate (Westbrook, Masle and Biju-Duval, 1984).

The Barbados Ridge complex is the easternmost portion of the Lesser Antillies subduction complex. At the adjacent deformation front the sediments overlying the Atlantic basement are offscraped and accreted onto the Caribbean Plate rather than subducted into a trench (Moore, Biju-Duval and Natlund, 1984). The ridge complex is characterized by large scale folding and thrust faulting of Cenozoic pelagic, hemipelagic and laterally transported clastic and biogenic material (Uchupi, 1975; Moore, Biju-Duval and Natlund, 1984).

Seismic profiles of the Barbados Ridge show an upper, highly deformed sequence underlain by a lower, layered sequence resting on the Atlantic basement

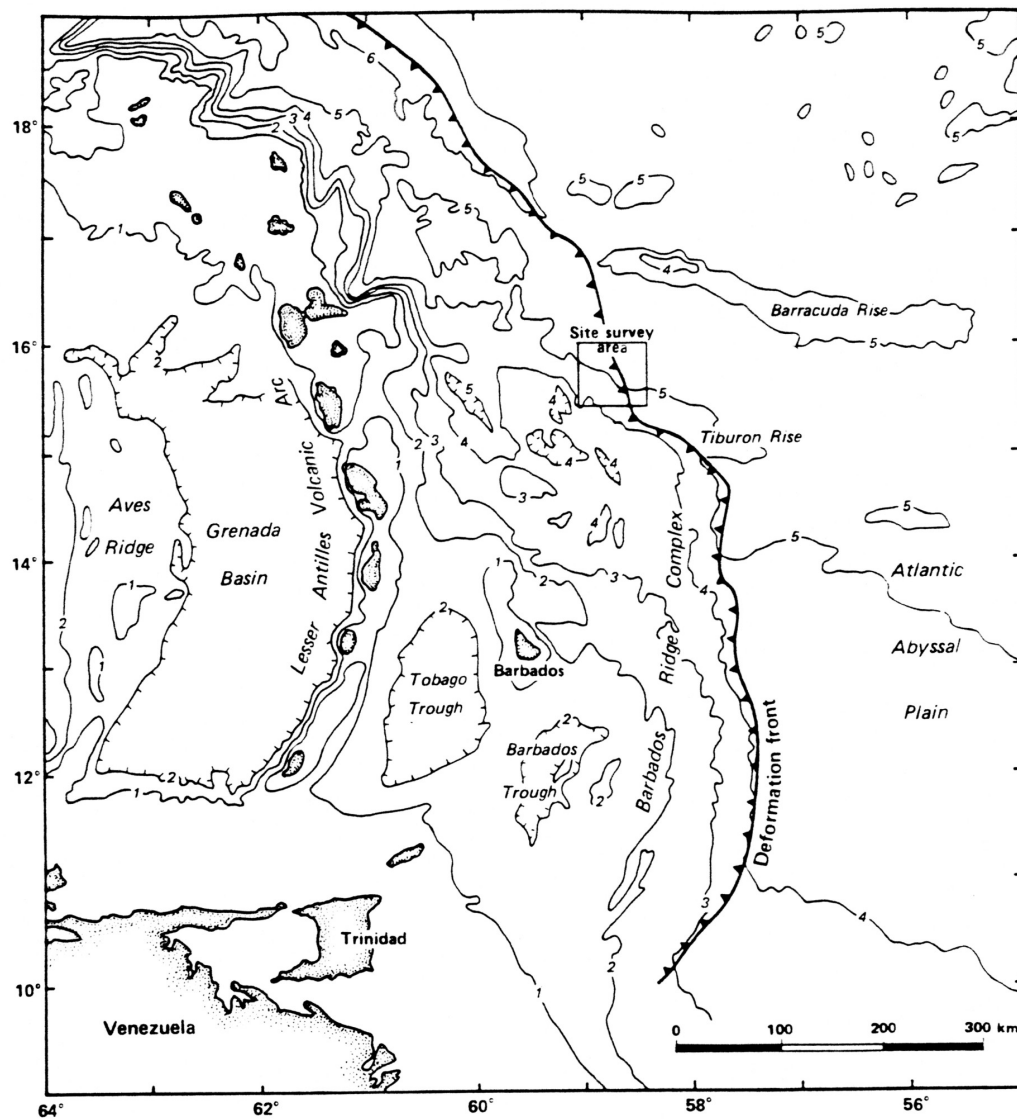


Figure 1. Location map of the site survey area at the deformation front of the Barbados Ridge Complex (modified from Ngokwey, Mascle and Biju-Duval, 1984).

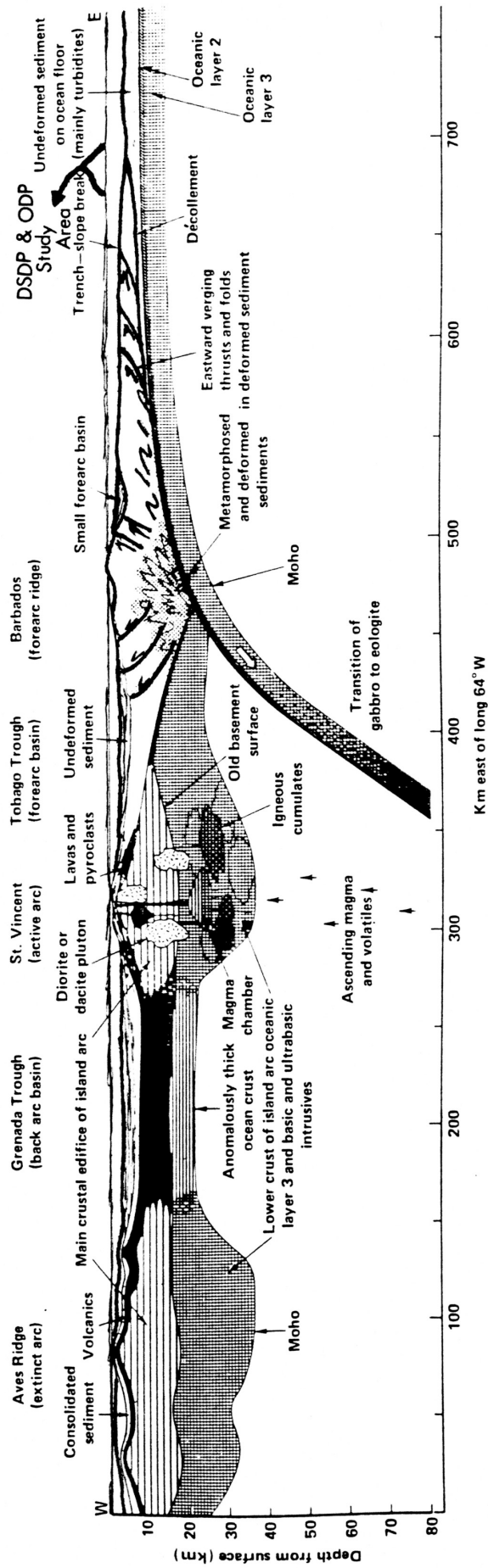


Figure 2. Cross-sectional model of the Lesser Antillies arc system through Barbados and St. Vincent (modified from Westbrook, Mascle and Bijou-Duval, 1984).

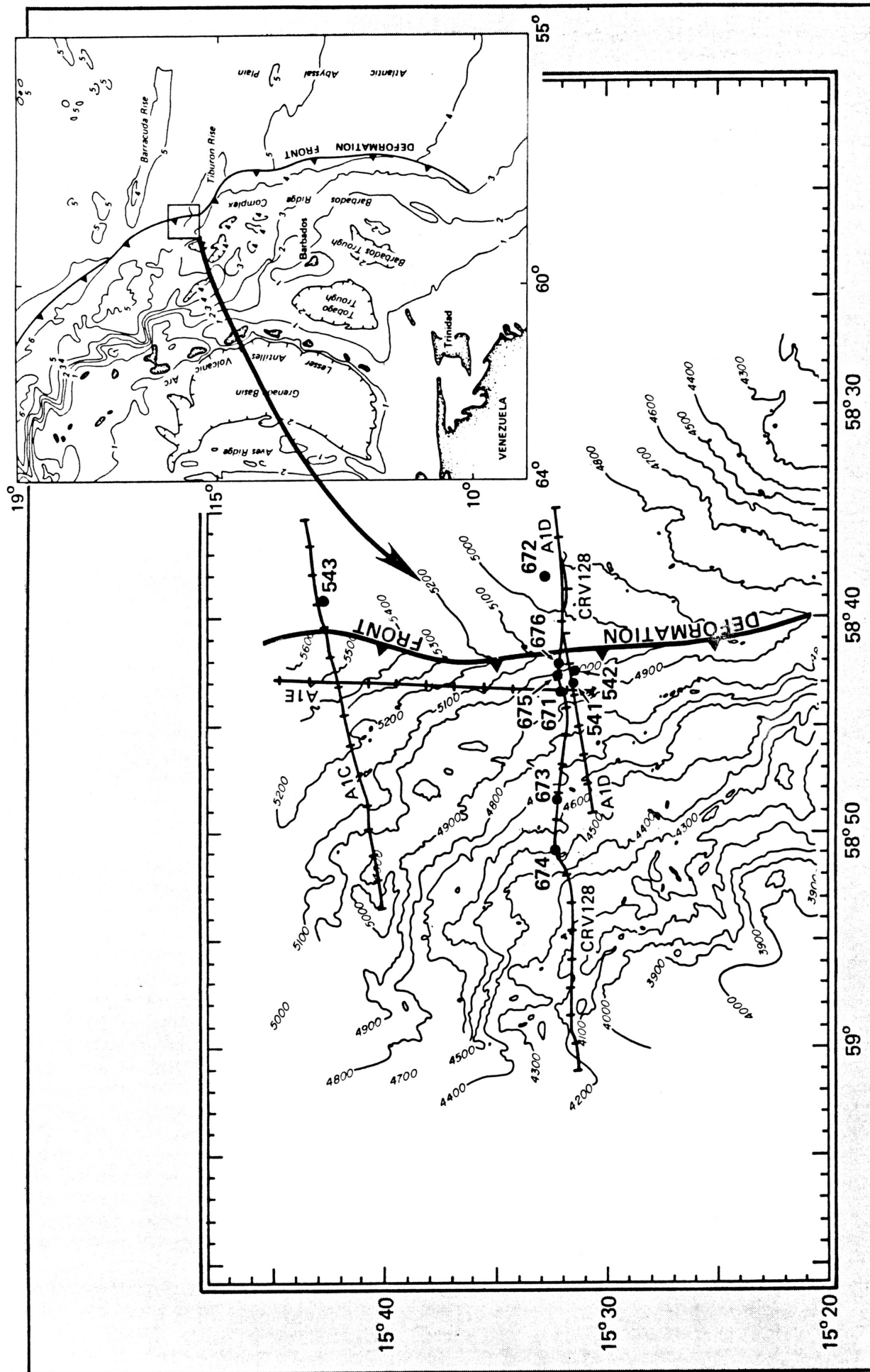


Figure 3. Location of drill sites for DSDP Leg 78A and ODP Leg 110 (from Mascle, Moore and others, 1987).

TABLE 1

Location of DSDP Leg 78A and ODP Leg 110 Sites

PROJECT	LEG	SITE	LAT.	LONG.	DISTANCE TO DEFORMATION FRONT	EAST OR WEST OF FRONT

DSDP	78A	541	15°32.1N	58°43.7 W	3 km	WEST
DSDP	78A	542	15°31.2N	58°42.8 W	1.5 km	WEST
DSDP	78A	543	15°42.7N	58°39.2 W	2 km	EAST
ODP	110	671	15°31.6N	58°43.9 W	5 km	WEST
ODP	110	672	15°32.4N	58°38.5 W	6 km	EAST
ODP	110	673	15°31.9N	58°48.5 W	12 km	WEST
ODP	110	674	15°32.3N	58°51.1 W	17 km	WEST
ODP	110	675	15°31.8N	58°43.0 W	2 km	WEST
ODP	110	676	15°31.9N	58°42.2 W	.5 km	WEST

(Moore, Biju-Duval and Natlund,1984). DSDP Leg 78A attempted to penetrate this boundary decollement (Masle, Moore and others,1987) with little success. They did, however find abnormally high borehole temperatures and higher than expected pore water concentrations of methane (Masle, Moore and others,1987; Davis and Hussong, 1984; Moore and Biju-Duval,1984). ODP Leg 110 was a second and more successful attempt to penetrate the decollement. As was the case with DSDP Leg 78A, this cruise also found high borehole temperatures and abnormal pore-ion concentrations. Leg 110 also found indications of lateral pore fluid movement and pore water pressures reaching almost lithostatic head (Masle, Moore and others,1987).

This paper will attempt to explain the observations made by the crews of DSDP Leg 78A and ODP Leg 110 near the deformation front bounding the Lesser Antillies subduction complex. After a brief description of the geologic setting of these observations, I will discuss the origin and effects of high pore pressures within the complex. This paper will also consider the origins of the methane, controls on fluid flow within the complex and the effect of fluid flow on the transmission of heat within the complex.

GEOLOGIC SETTING

The Lesser Antillies subduction complex forms the eastern margin of the Caribbean Plate (Westbrook, Masle and Biju-Duval,1984). The complex is convex to the east and has a total length of about 750 km. Below 16°N the complex is about 450 km wide, narrowing at 16°N to a width of 150 to 200 km (Uchupi,1975; Moore, Biju-Duval and Natlund,1984). The western margin of the complex is the

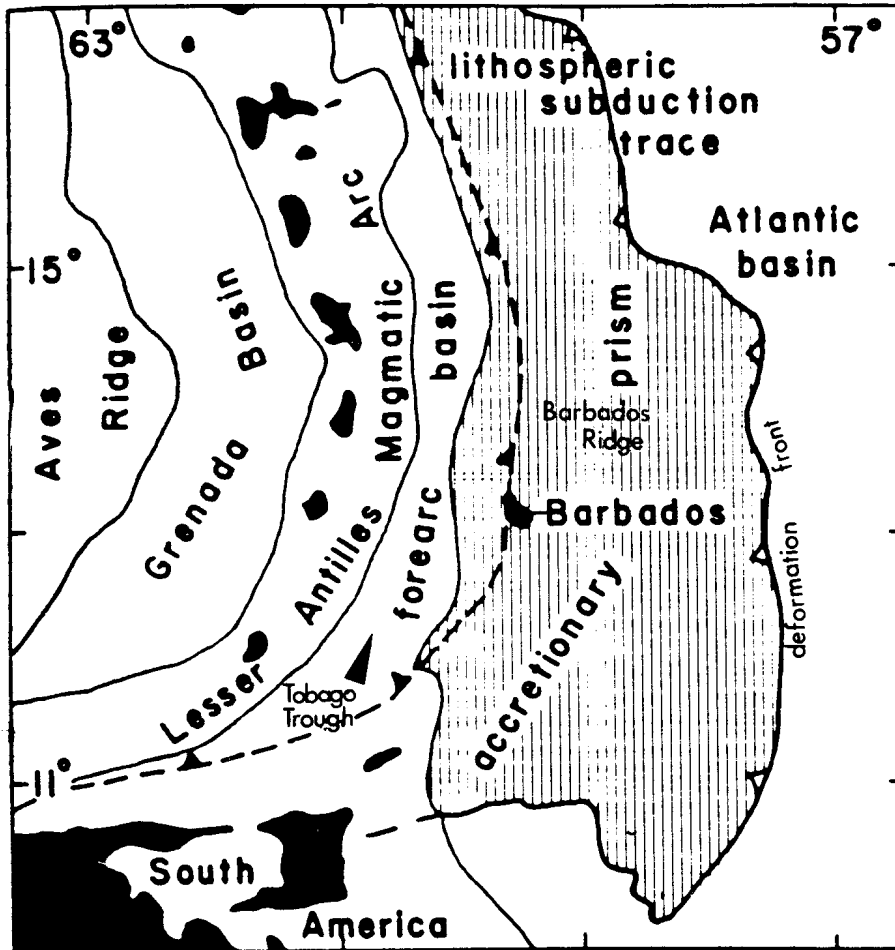


Figure 4. Physiography of the Lesser Antillies arc system (modified from Larue and Speed, 1984).

Lesser Antillies Ridge, containing the islands of the Lesser Antillies Island Arc. East of the Lesser Antillies is the Tobago Trough, possibly an active forearc basin, as indicated by the flat-lying sediments covering the older deformed sediments (Uchupi,1975). The easternmost portion of the accretionary complex is the Barbados Ridge, at the actively accreting edge of the plate. It is composed of an upper, deformed sequence overlying a lower, layered sequence which in turn lies directly on the oceanic basement (Moore, Biju-Duval and Natlund,1984). The island of Barbados is the only emergent portion of the Ridge (Uchupi,1975). East of the deformation front, which marks the region where the Atlantic sediments are being offscraped and accreted, lie two rises, the Barracuda north of 16°N and the Tiburon south of 16°N.

ODP Site 672 (Figure 5) was drilled 6 km east of the deformation front as an oceanic reference section. The core sampled 500 m of the 800 m of Atlantic sediments that overlie the Senonian age crust (Mascle, Moore and others,1987). The sediments of this section range from Pleistocene to lower Eocene. The Lower Pleistocene to Lower Miocene interval is composed of massive hemipelagic claystones and mudstones with many ash layers from the volcanoes of the Lesser Antillies arc (Mascle, Moore and others,1987). The Upper Oligocene to middle Eocene interval is composed of alternating layers of calcareous mudstone, marl, limestone, claystone, siltstone and sandstone that record lateral transport of clastics from South America and biogenic material from the Tiburon Rise, with some background hemipelagic sedimentation (Mascle, Moore and others,1987). The lowermost middle Eocene to Lower Eocene interval is siliceous claystone (Mascle, Moore and others,1987).

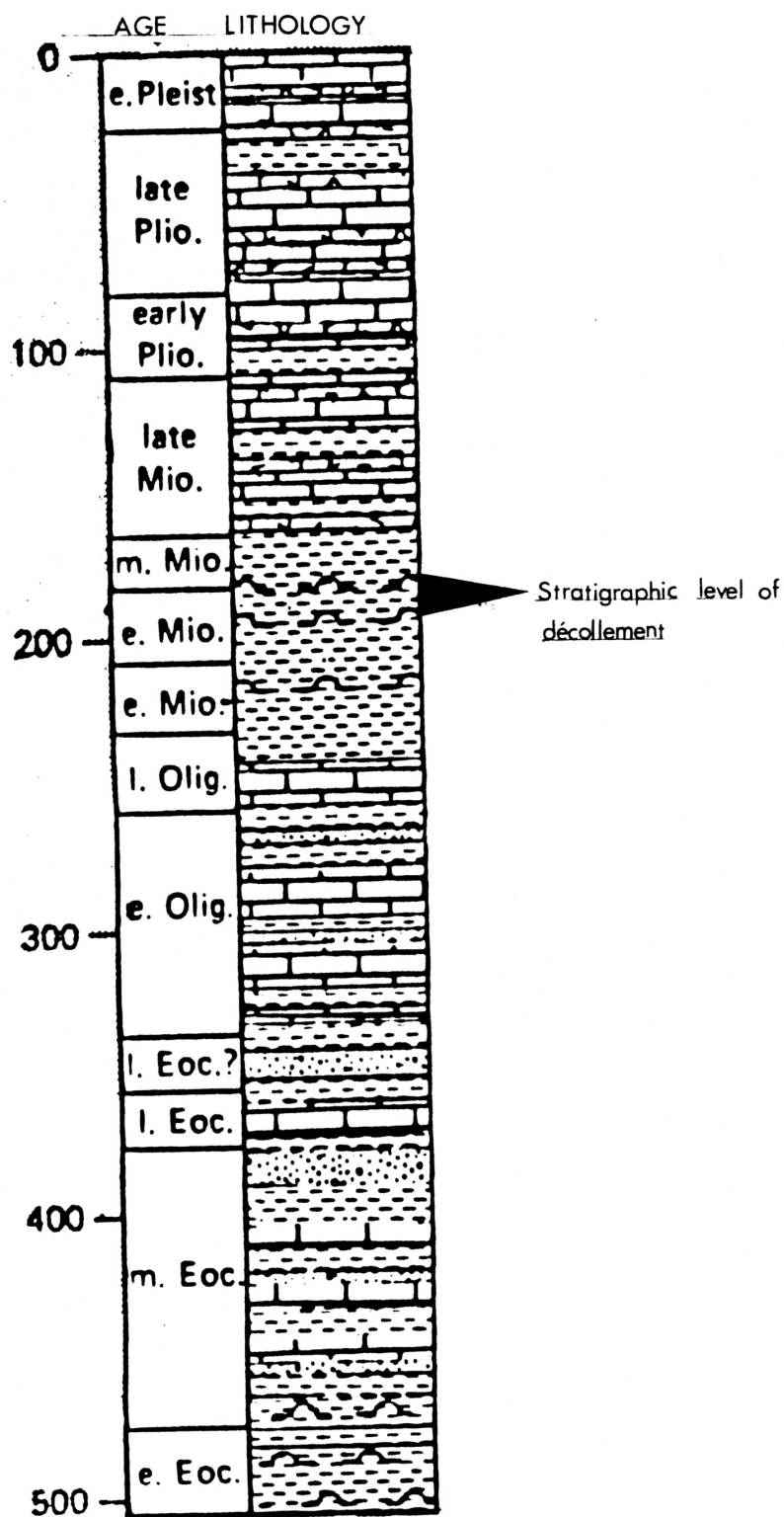


Figure 5. Stratigraphy of Site 672, ODP Leg 110 (modified from Mascle, Moore and others, 1987).

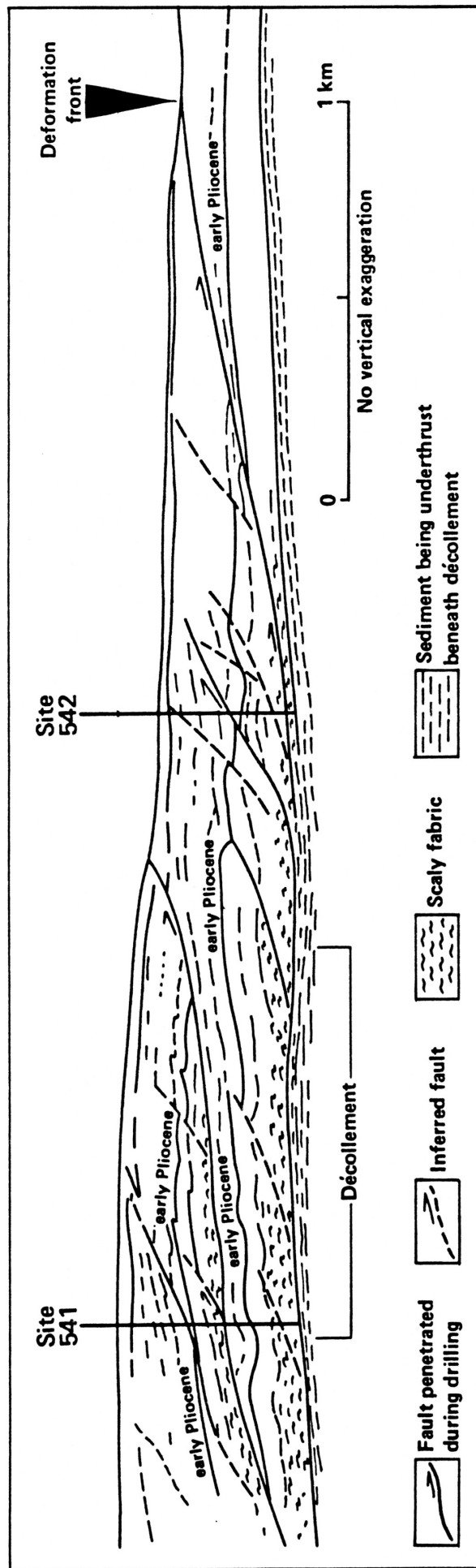


Figure 6. Geologic cross section showing detail of offscraped sediments (modified from Moore and Biju-Duval, 1984).

These oceanic sediments are disturbed at the deformation front as they are scraped off of the Atlantic Plate and accreted to the Caribbean Plate (Figure 6). The most prominent structural feature is the decollement which separates the upper, highly deformed sediments from the lower, layered sediments that will eventually be subducted. This structural zone occurs in sediments of early Miocene age and indications of an incipient decollement zone are found in the reference core from Site 672 (Masle, Moore and others,1987). Westward dipping thrust faults splay off from the decollement (Moore and Biju-Duval,1984). Seismic profiles show a high amount of folding within the ridge complex. This is confirmed by the wide range of dips and overturned section seen in the cores. The cores from Sites 541 and 542, DSDP Leg 78A, also contain cataclastic shear zones, stratal disruptions and scaly foliation (Lundberg and Moore,1986). These structures are the result of the compressional stresses of accretion (Moore and Lundberg,1986).

HIGH PORE PRESSURES

Both the DSDP and the ODP legs that sampled the Barbados Ridge Complex reported indications of higher than expected pore pressures. At Site 542, a maximum sustained pressure of 300 to 350 psi (2.06 to 2.4 MPa) was measured (Moore and Biju-Duval,1984). The Leg 110 crew (Masle, Moore and others,1987) reported that at Site 675 dilatant rhodochrosite-filled veins were encountered. The Leg 78A crew also reports that the sediments were underconsolidated (Shi and Wang,1985). Seismic profiles indicate that mud volcanoes and diapirs are present, especially in the southern part of the complex where the sediments are thicker (Shi and Wang,1985; Uchupi,1975). These findings indicate pore

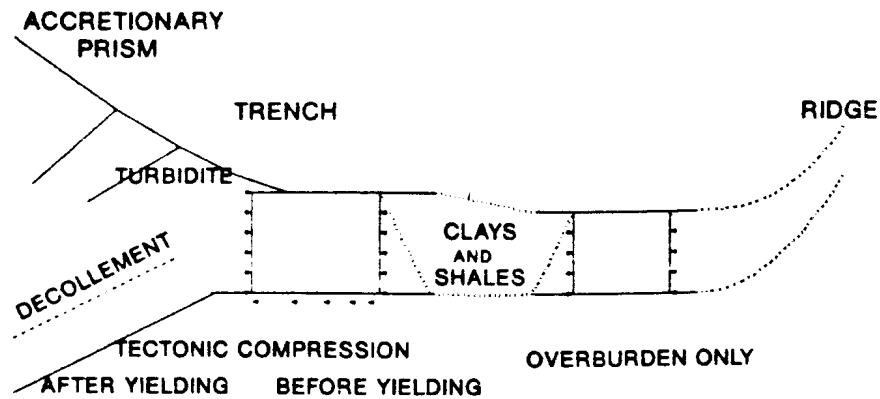


Figure 7. Schematic diagram showing the three deformational stages of sediments on a subducting plate (from Shi and Wang, 1985).

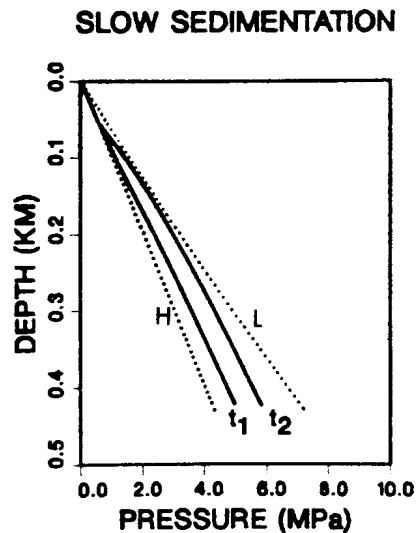


Figure 8. Model for pore pressure evolution with slow sedimentation. Curve t_1 shows result of stage 1, and curve t_2 shows result at end of stage 2. H and L are hydrostatic and lithostatic pressure, respectively (from Shi and Wang, 1985).

pressures approaching lithostatic head.

Shi and Wang (1985) have proposed three stages in the development of pore pressure in subduction complexes (Figure 7). The first stage is during pelagic sedimentation at low sedimentation rates. During this stage, stresses from tectonic compression are negligible and pore pressure is determined by overburden alone. During stage two, the sediments are elastically deformed as they approach the deformation front. Tectonic compression increases as a result of resistance from the accretionary prism and shear from the oceanic basement of the driving plate. Thick sequences of coarser grained clastics add areas of higher permeability and porosity. In the third stage, the sediments are intensely deformed as they are accreted to the overriding plate.

Shi and Wang (1985) used two models to look at the development of pore pressures. The first model, involving low sedimentation rates, approximates the history of the Barbados Ridge sediments at the latitude of the DSDP and ODP coring sites. This model indicates that pore pressure most closely approaches lithostatic pressure not at the bottom of the sediment column but near the middle of the column under the low permeabilities observed at the DSDP sites (Marlow, Lee and Wright, 1984). This is also the approximate position of the decollement within the Barbados Ridge sediments (Figure 8).

ORIGIN OF METHANE AT THE BARBADOS RIDGE COMPLEX

Pore fluid observations from both the ODP and DSDP cruises showed higher than expected concentrations of methane. Such observations have also been made

at the accretionary complex off of the Oregon coast (Ritger, Carson, and Suess,1987; Kulm and others,1986). Unlike the Oregon sites, the samples from the DSDP cores contain the heavier hydrocarbons butane through hexane (Claypool,1984). These hydrocarbons were found dispersed within the sediments in concentrations of 100 - 800 ppb (Claypool,1984).

Although organic content of the sediment is low (<0.3%), the volume of accreted sediments is large enough to account for the amounts of hydrocarbons observed. Hunt (1979) indicates that for thermal generation of methane to occur temperatures of 75° C are required, with peak generation around 120°C. These temperature can be generated within the deeper portions of the subduction complex. The samples from DSDP cores contain the heavier hydrocarbons C₂-C₆, which indicate that the methane is thermogenic; methane being the only hydrocarbon produced by microbial reactions (Ritger, Carson, and Suess,1987). Claypool (1984) found an increase in hydrocarbon content with depth, indicating that the hydrocarbons are formed in situ by diagenesis of organic matter. Methane is, in the case of the Barbados Ridge, probably generated throughout the lower portion of the complex, especially in the earlier accreted sediments, and concentrated in the portions of the sediment column with the highest porosity.

One effect of the presence of excess methane is that its oxidation releases carbon which is then available for the precipitation of carbonates. Ritger, Carson and Suess (1987) sampled authigenic carbonates from the Oregon accretionary complex, finding authigenic pyrite within the carbonates. This indicates that the methane is oxidized within the sulfate reducing zone by the reaction:

Core-section	Sub-bottom depth (m)	10 ⁻⁹ vol. gas per vol. sediment (nl/L or ppb by vol.)							Total	C ₁ /C ₂ ^a
		C ₂	C ₃	i-C ₄	n-C ₄	i-C ₅	n-C ₅	n-C ₆		
Hole 541										
3-2	30	4	n.d.	n.d.	1	n.d.	7	n.d.	12	n.a.
10-3	100	2	2	n.d.	n.d.	7	16	n.d.	27	n.a.
27-6	270	75	20	16	11	3	18	31	174	n.a.
39-5	360	89	27	84	2	2	n.d.	65	270	n.a.
42-3, 4	387	287	80	29	23	n.d.	14	48	480	22
48-4, 5	444	490	140	22	19	12	7	n.d.	690	17
Hole 542										
H2-4	150	88	21	42	7	16	1.2	n.d.	176	30
1-5	210	47	32	36	5	4	n.d.	27	151	17
Hole 542B										
4-3	263	32	5	6	n.d.	n.d.	n.d.	n.d.	43	n.a.
10-2	318	82	22	14	6	n.d.	n.d.	17	140	10
Hole 543										
5-2	41	168	84	26	45	11	13	38	385	18
26-2	241	42	37	22	6	1	n.d.	n.d.	110	n

Note: n.d. = not detected. n.a. = not analyzed.

^a Estimate of methane : ethane ratio from separate analysis.

Table 2. C₂-C₆ hydrocarbon gas content of core samples, DSDP Leg 78A (from Claypool, 1984).

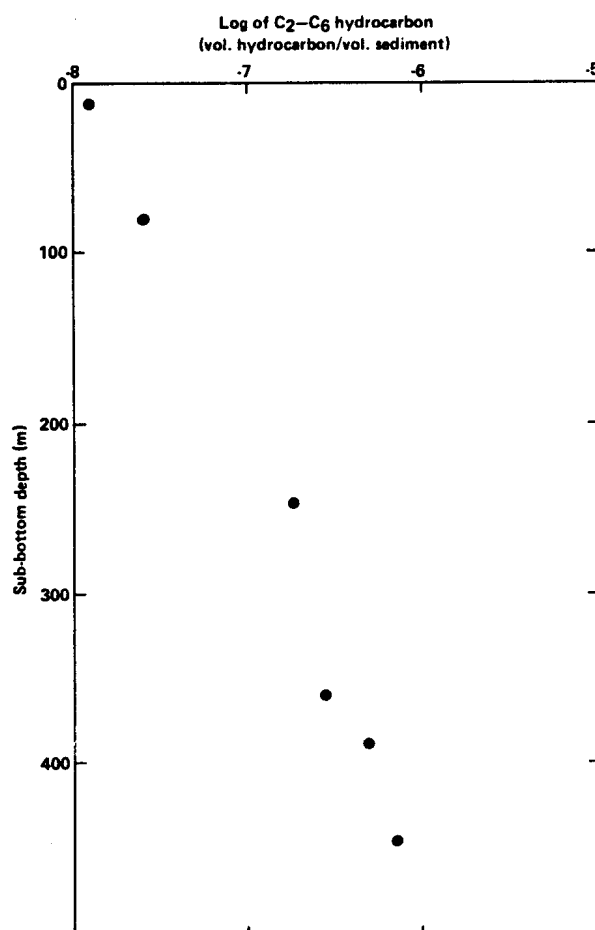
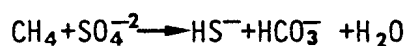


Figure 9. Plot of log C₂-C₆ hydrocarbon content vs. burial depth for core samples, Site 541, DSDP Leg 78A (from Claypool, 1984).



(Ritger, Carson and Suess, 1987). This reaction also provides hydrogen sulfide for the production of the pyrite in the samples. Speed, Torrini and Claypool (1985) found calcitized fault zones in deformed sediments from the Barbados Ridge Complex exposed on the island of Barbados. These carbonates have $^{13}\text{C}/^{12}\text{C}$ isotopic ratios which indicate that the carbon is derived from organics (Speed, Torrini and Claypool, 1985), suggesting that they were precipitated by the oxidization of methane. They also found evidence that the carbonates were precipitated prior to cessation of faulting, while the fault zone served as a dewatering conduit for the complex. Claypool (1984) reports that pore water from Sites 541 and 542 is enriched in ^{34}S , while the pore water from Site 543 has essentially the same ^{34}S content as seawater. This indicates that the oxidation of organics is still an active process within the Barbados Ridge Complex.

FLUID FLOW WITHIN THE BARBADOS RIDGE COMPLEX

Geothermal observations at DSDP sites 541 and 542, west of the deformation front, were inconclusive (Davis and Hussong, 1984) but indicate that the geothermal gradient within the offscraped sediments are surprisingly high. At site 541, temperatures of 20.4°C were calculated (Davis and Hussong, 1984) at a depth of 170 m subbottom. Along with the near lithostatic pressures measured for the fluids near the decollement (Moore and Biju-Duval, 1984) this indicates that pore fluids from deeper within the accretionary prism are being forcefully expelled along active faults.

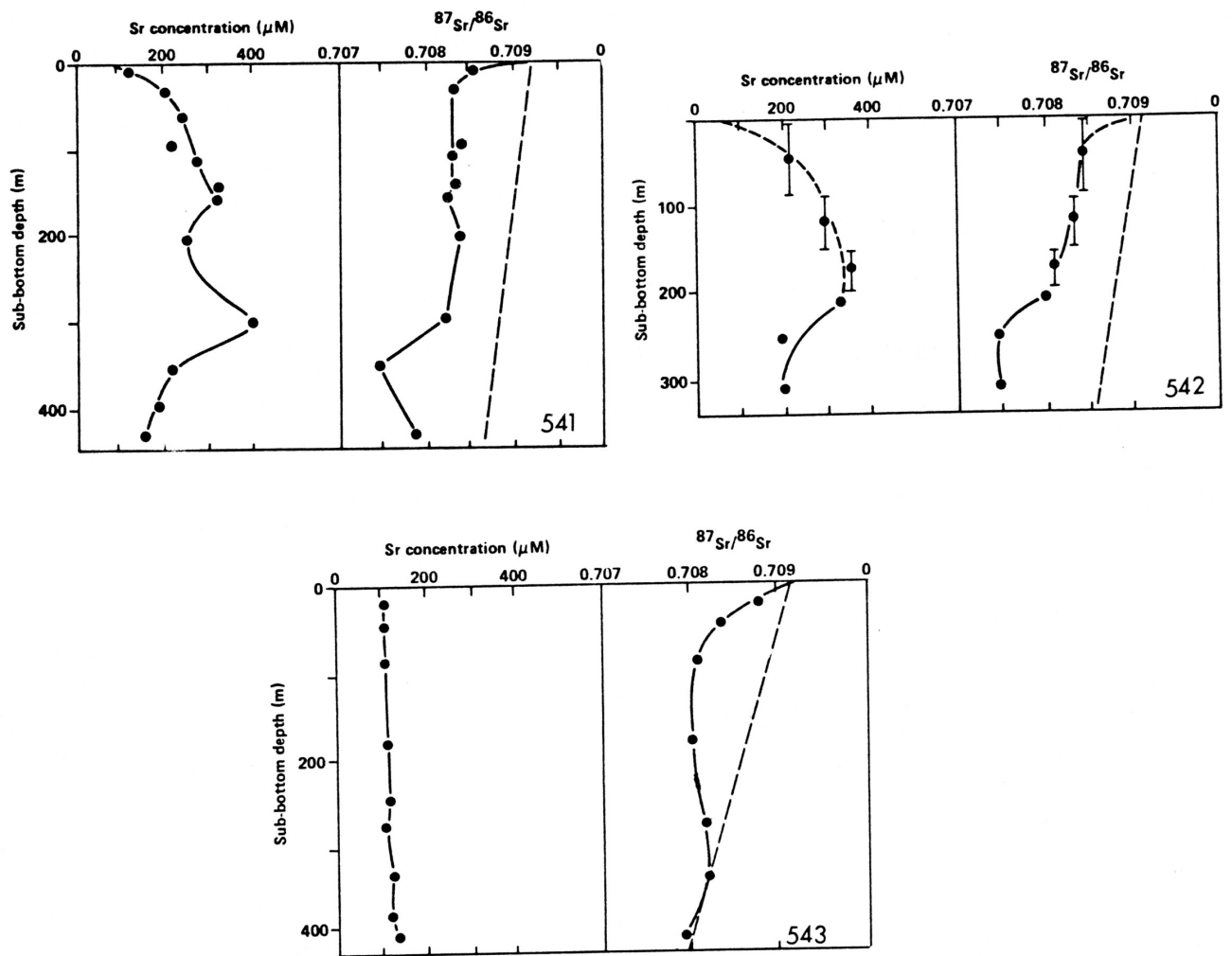


Figure 10. Strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ curves for Sites 541, 542 and 543, DSDP Leg 78A. Dashed lines are for contemporaneous seawater (modified from Giekes, Elderfield, Lawrence and LaKind, 1984).

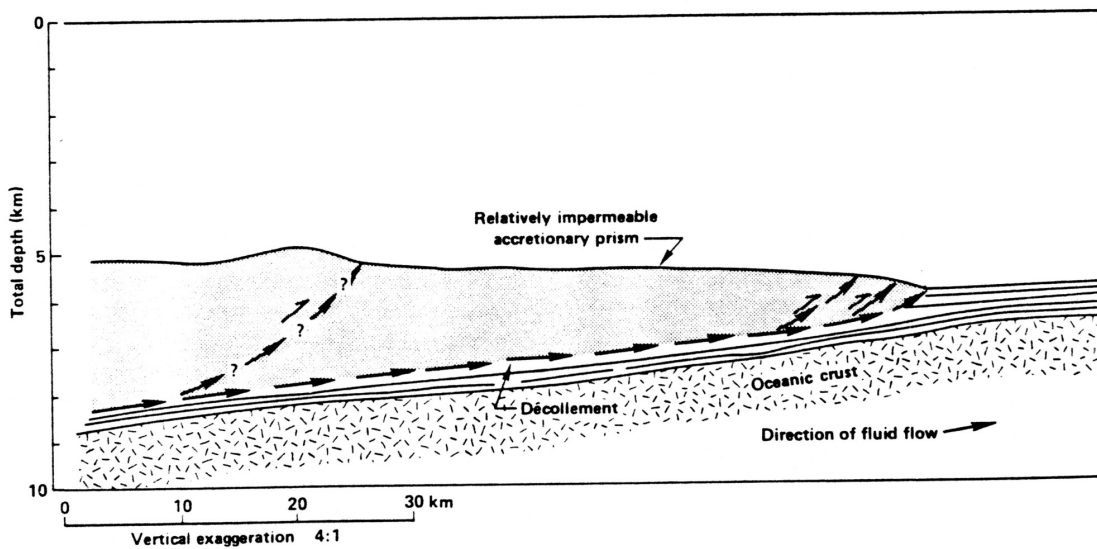


Figure 11. Schematic of fluid flow within the Barbados Ridge Complex (modified from Moore and Biju-Duval, 1984).

Carson and Berglund (1986) showed experimentally that dewatering occurs at the bottom of a sediment column under convergent horizontal stress. However, their results indicate vertical advection of pore fluids through the sediment water interface. This is contrary to isotopic evidence from DSDP Leg 78A observations. Interstitial water data from pore fluids show trends indicating that advection is not the escape route of fluid from within the complex (Gieskes, Elderfield, Lawrence and LaKind, 1984). This is based on dissolved strontium concentrations and $^{87}\text{Sr}/^{86}\text{Sr}$ distribution curves from drilling sites on both sides of the deformation front.

Cloos (1984) proposed that landward dipping seismic reflectors act as active dewatering conduits within accretionary wedges. Thrust faults splaying from the basal decollement would suggest that these are conduits for fluids driven off during dewatering. Evidence from exposures of the complex on Barbados (Speed, Torrini and Claypool, 1985) indicates that the splay thrusts serve as conduits for the dewatering of the accretionary complex. The high pore pressures coupled with the high (75%) porosities (Moore and Biju-Duval, 1984) detected within the decollement indicate that this is the main dewatering conduit for the complex, supplying water to the thrust faults and the incipient decollement to the east of the deformation front.

SUMMARY

As sediments are accreted to the overriding plate, tectonic and loading pressures force dewatering of the earliest accreted sediments. As accretion progresses, a decollement forms along a weak bedding zone. In the case of the

Barbados Ridge, this is a Miocene mud-rich interval (Moore and Biju-Duval,1984). Along this deformation zone pore pressures build to almost lithostatic pressures. Porosities and permeabilities within this zone and the thrust faults splaying from it allow water from deeper within the complex to migrate to the sediment-water interface. These pore fluids conduct heat and concentrate thermogenic methane from within the accreted sediment packages to the sea floor. As data from DSDP Site 543 indicates (Biju-Duval, Moore and others,1984) the overpressured fluids may migrate past the deformation front, creating mud volcanoes in the sediments yet to reach the accretionay wedge.

Studies of the Oregon subduction zone have shown that vented pore fluids have two major effects (Ritger, Carson, and Suess,1987; Kulm and others,1986). The most obvious is the existance of vent communities based on the bacterial decomposition of hydrogen sulfide produced by the oxidation of methane within the sulfate reducing zone. The second effect is the production of authigenic carbonates from carbon released by these same oxidation processes. Evidence of this process has been reported from exposures of the complex on Barbados (Speed, Torrini and Claypool,1985). These two processes could be active along venting sites at the Barbados Ridge Complex.

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